Advanced Vehicle Pneumatic Suspension Systems Yield Cost Savings While Increasing Safety and Performance

Larry Huetsch and Ken Maciejewski
Pneumatics Division North America
Global Mobile Systems
850 Arthur Avenue, Elk Grove Village, IL 60007-5215
Larry.Huetsch@parker.com, Ken.Maciejewski@parker.com

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Introduction

Current vehicle pneumatic suspension systems are pressurized to maintain a vehicle at a pre-selected ride height regardless of wheel loading. Air springs at each wheel location support the load. Mechanical leveling valves are mounted to the frame (sprung portion of the vehicle), while a linkage arm provides attachment to the axle of the vehicle (see Figures 1 & 2).

Figure 1 – Front suspension configuration

Figure 2 – Rear suspension configuration

Generally one leveling valve per axle is used. The vehicle’s pre-selected ride height is simply maintained via the mechanical leveling valve increasing or exhausting air spring pressure, relative to its neutral position. The leveling valve flow rate is proportional as it reaches the neutral position, resulting in less air flow for small height adjustments and increased air flow for larger height adjustments. The leveling valves may have a built-in mechanical delay to help prevent uncontrolled suspension adjustments while driving on rough roads and at highway speeds.
The vehicle’s braking system air supply is protected against potentially excessive air depletion from the suspension system (i.e. component failure creating a leak down) by incorporating a pressure protection valve. The pressure protection valve (see Figure 3) threads into the air brake supply reservoir outlet, and subsequently controls supply air to the suspension system reservoir and other accessories. If the pressure in the air brake supply reservoir falls below a preset pressure, supply air to the suspension system is automatically isolated from the air brake system. This is necessary to keep the emergency spring brakes or parking brakes from an uncontrolled automatic engagement. Air pressure above a preset value, usually around 65 psig, maintains the spring brakes in the off/released position during normal driving situations.

*Figure 3 – Typical PPV product styles*

The kneeling operation, as required for public transit buses, is accomplished by the integration of a kneeling valve into the existing air suspension system. The kneeling valve lowers the step-in height at entrance or exit locations, while also lowering the incline angle on the deployed ramp for wheelchair ingress/egress. A minimum 1:6 slope ratio for the wheelchair ramp angle is required to meet the latest Americans with Disabilities Act (ADA) requirements (see Figure 4).

*Figure 4 – Typical transit wheelchair ramp*

The kneeling valve typically only controls or lowers the front passenger side corner of the bus. The option of lowering the entire vehicle front or only the passenger side is an available feature. The kneeling circuit generally incorporates an exhaust valve and a supply air inlet valve for accelerated kneeling and raising operation times. The kneeling valve assembly integrates all of this functionality into a manifold housing, therefore facilitating a clean and efficient installation (see Figure 5).

*Figure 5 – Kneeling valve circuit installation schematic (upper) and complete kneeling valve assembly (lower)*
Active Electronic System Approach

Air spring pressure can be more efficiently controlled with the integration of electronics, thus delivering important features and benefits to vehicle performance. Each air spring, and thus each wheel location, can be independently controlled by the integration of an electronic control system to operate each corresponding pneumatic control valve. The diagram in Figure 6 demonstrates centralized pneumatic control; however, distributed pneumatic control is more tailored for a true active electronic system. With distributed pneumatic control (i.e. pneumatic control valves located near, or integrated into, each air spring), the suspension system can respond quickly with more precision. The electronic portion of the system would consist of an ECU, dash controls or touchscreen, linear or rotary position transducers, pressure transducers and wheel speed sensors (see Figures 7 & 8). Air spring pressure data can translate into load values, position data can translate into vehicle height, and wheel speed data can translate into vehicle speed or relative independent wheel speed. The suspension system can quickly and accurately respond to the changes from this electronic input data.

Wheel loading at each location can be determined by mapping the actual wheel load values (i.e. tire weight) versus air spring pressure at ride height. This data can be programmed and stored in the ECU for active analysis and monitoring during vehicle operation.

Enhanced Safety

This information can also be utilized to enhance vehicle loading efficiency on trucks or trailer applications. Another benefit is identifying unsafe loading conditions and taking preventative measures accordingly, such as limiting speeds and other performance capabilities. Active vehicle wheel loading data and adjustments (i.e. increasing or decreasing air spring pressure) can also be utilized to improve braking, traction and stability control performance.
As discussed previously, vehicle height can easily be adjusted and controlled to meet ADA requirements on public transportation vehicles. Additionally, semi-tractor fifth wheel height can be lowered or raised to facilitate an easy, safe and secure semi-trailer hookup (see Figure 9).

![Figure 9 – Semi-tractor fifth wheel](image)

### Fuel Efficiency and Savings

With the rising cost of fuel, it becomes increasingly imperative to look for ways to conserve fuel. With an active electronic suspension, vehicle ride height can be lowered at highway speed to decrease aerodynamic drag, thus yielding an increase in fuel efficiency. The impact can be significant when operating a vehicle 100,000 miles or more per year. Referencing Figure 11, optimum fuel efficiency can be achieved by reducing frontal aerodynamic drag (\(\frac{2}{3}\) of the 53% total vehicle energy consumption - yielding a 35% capture). Consider the following cost saving yield example:

- Diesel fuel costs \(\approx \$3.75\) per gallon
- Fuel consumption \(\approx 6\) miles per gallon
- Aerodynamic drag reduction \(\approx 3.5\%\)
  - Lowering vehicle by 4"
- Fuel mileage improvement yield \(\approx 1.5\%

- Potential fuel cost savings \(\approx \$925\) per yr.
  - 100,000 miles per yr. operation

![Figure 10 – Vehicle Speed vs. Hp Consumption](image)

![Figure 11 – Usable Energy Consumption at Highway Speed](image)

The following is extracted information from a study conducted by the Lawrence Livermore National Laboratory (project I.D. # VSS006) for the DOE in 2010 (see Figures 10 & 11).

As reference:

\[
F_D = C_D \frac{A p V^2}{2}
\]

\(F_D\) = drag force, \(C_D\) = drag coefficient, \(A\) = effective frontal area, \(p\) = air density and \(V\) = relative velocity.

Monitoring air spring pressures correlates to real-time vehicle load, and controlling the air spring pressure enables regulation of the load and height at each wheel location. On-highway applications (i.e. trucks, trailers, buses, etc.) could be tuned differently from off-road applications (i.e. dump trucks, utility vehicles, etc.). A vehicle can also be programmed to run in multiple operating conditions, seamlessly transitioning via the electronic control. This creates an intelligent suspension system since it is capable of responding to various inputs and achieving active control.
**Energy (Air Pressure) Conservation**

Energy conservation in a pneumatic system correlates to conservation of air pressure. Inevitably, engine power or battery power is required to drive a compressor and produce air pressure. In existing mechanical leveling valve controlled suspensions, the valve’s objective is to continually maintain vehicle ride height. Thus, the valve is constantly reacting to changes in road conditions by discharging (exhausting) or charging (pressurizing) the air spring. The leveling valve’s construction allows for proportional flow in both directions with a dead band, or built-in “delay”, as ride height is approached (see Figure 12).

To put this into perspective, +/- 1.5° of dead band correlates too approximately +/- 3/16" in height displacement between the axle and frame. Referring to Figure 12, a flow rate of 1.5 scfm is either discharged or charged to the air spring with a ½" deflection (4° angle of arm rotation). A vehicle operating on rough terrain can induce frequent and substantial ride height adjustments, resulting in excessive air pressure (energy) consumption. This recurrent height calibration and air pressure consumption is inherent to a mechanically height controlled suspension system.

An electronically controlled suspension system can actively adapt to varying road terrains and driving conditions, while adjusting ride height calibration only when necessary. An active system can also be configured to operate in a passive state, whereby the suspension system resembles a standard leaf suspension while in motion. Therefore, the air spring pressure is captive which will conserve air pressure energy while in transit.

The other main drawback to a mechanically height controlled suspension system is the complete exhaust of the air springs when kneeled. This is especially important in the paratransit market where kneeling operations can exceed 30 operations per hour. Air consumption and regeneration are critical aspects pertaining to the overall health, sustainability and longevity of the system. An electronically controlled suspension system can capture air pressure in each air spring when fully kneeled height is achieved. Each air spring can maintain considerable residual air pressure when the vehicle has reached its fully kneeled position (see Figure 13).

**Figure 12** – Typical Flow vs. Angle of Misalignment on a mechanical height control valve (+/- 1.5° of dead band or delay)

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**Figure 13** – Pressure vs. Time graph of a vehicle undergoing a full kneel sequence with integrated electronic controls enabled to capture residual air spring pressure
The conservation of air spring pressure when kneeling can have a considerable impact on air pressure regeneration time, compressor usage and duty cycle. When kneeling an entire vehicle (i.e. 4 total air springs), a large amount of stored energy is lost in the form of exhausting air pressure. Capturing this stored energy has a twofold benefit: stored energy conservation leading to reduced compressor activation and faster recovery time to raise the vehicle.

Recovery time is defined as the time to adequately raise the vehicle to a height that is safe to shift into gear and drive away. This can be a significant benefit to many properties and municipalities because frequency of stops and quicker route times equal increased revenue. A longer wait for the vehicle to reach drive away height results in lost time of the vehicle in service and fewer customer stops or pick-ups. Consider the following actual comparison between suspension systems with regards to recovery time (i.e. this represents a heavily used vehicle route with frequent stops):

- Vehicle stops ≈ 20 kneels per hour
- Vehicle operation ≈ 16 hours per day
- Current drive away time ≈ 8 sec
  - Mechanically controlled system
- New drive away time ≈ 2 sec
  - Electronically controlled system
- 6 sec time savings @ each stop
- Results in over 10 extra stops per day
- Improved vehicle route efficiency ≈ 3%

Time savings, additional stops and improved route efficiency can all produce increased revenue for the property or municipality. For vehicles with multiple and frequent stops (i.e. shuttle bus services at airports), every second is valuable.

Air pressure regeneration is a corollary effect to capturing residual air spring pressure when kneeling or lowering a vehicle. All of the air that is exhausted during a kneeling sequence must be regenerated through the use of an air compressor. Therefore, efficiently conserving this air pressure can lead to energy savings and decreased compressor usage. Since vehicle air compressors are either driven by the engine or electrically via battery power, vehicle energy is required to power the air compressor. With the air compressor requiring less cycling, vehicle energy can be applied or stored for other functions. Referring to Figure 14, air compressor recharging times decreased by 35-45% utilizing a smart electronically controlled suspension system.

Figure 14 – Compressor Recharge Time Comparison Graph

Conservation of energy serves an important role by reducing the cost of lost energy, while also positively impacting the overall longevity and efficiency of the entire system. This significantly contributes to lower operational costs over the life of the vehicle.
Future Developments

Locating the air spring control valve close to the air spring enhances the overall suspension system response time, which unlocks the countless features and benefits discussed previously. There are electronic suspension systems currently on the market, but they do not sufficiently utilize all of the vehicle’s component capabilities.

Generation 1 of our system approach migrates away from simplified mechanical ride height control and into electronic control. It places the control valve in close proximity to the air spring, while incorporating real-time positioning and load sensing. Generation 2 furthers the system evolution into a true “plug-and-play” modular design concept – integrating the control valve, height sensor and pressure transducer into the air spring housing itself (see Figure 15).

Conclusion

The integration of electronic controls into pneumatic suspension systems can lead to new and significant business opportunities. Many of these applications can already be implemented by combining standard Parker components such as ECD’s Vansco or IQAN electronic controllers, position transducers and PDN’s Viking Xtreme valves. The vehicle’s current ABS wheel sensors can also be monitored for wheel speed information, and the stability control system can be enhanced by the addition of real time wheel loading data.

Upgrading a vehicle from standard suspension to an advanced pneumatic suspension system has shown to yield cost savings over the life of the vehicle in the form of fuel savings, energy consumption, and durability. An advanced suspension system can provide the solution to the recurring questions concerning energy conservation, system efficiency, safety and real-time diagnostics of vehicles. The value of these suspension advancements can be realized as a deeper understanding of how vehicle performance and efficiency is related to suspension control characteristics. Parker Hannifin’s vision and goal is to advance the vehicle transportation industry by engineering systems which will enhance vehicle performance, efficiency and safety.